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Production and propagation of heavy hadrons in air-shower simulators

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Abstract

Very energetic charm and bottom hadrons may be produced in the upper atmosphere when a primary cosmic ray or the leading hadron in an extensive air shower collide with a nucleon. At $E \approx 10^8$ GeV their decay length becomes of the order of 10 km, implying that they tend to interact in the air instead of decaying. Since the inelasticity in these collisions is much smaller than the one in proton and pion collisions, there could be rare events where a heavy-hadron component transports a significant amount of energy deep into the atmosphere. We have developed a module for the detailed simulation of these processes and have included it in a new version of the air shower simulator AIRES. We study the frequency, the energy distribution and the depth of charm and bottom production, as well as the depth and the energy distribution of these quarks when they decay. As an illustration, we consider the production and decay of tau leptons (from D_s decays) and the lepton flux at PeV energies from a 30 EeV proton primary. The proper inclusion of charm and bottom hadrons in AIRES opens the possibility to search for air-shower observables that are sensitive to heavy quark effects.

1 Introduction

Air-shower simulations are an essential tool in cosmic-ray physics [1, 2]. Primary particles can reach the Earth with energies of up to 10^{11} GeV, a scale well above the one explored at colliders. The simulation of these events requires then an extrapolation of the *known* physics that could be affected by several factors. On one hand, there could be new particles or interactions not accessible at lower energies. In this sense, cosmic rays may offer opportunities in the search for strong TeV gravity [5], new neutrino interactions [6], or long-lived massive particles [7]. On the other hand, cosmic-ray energies may imply a regime where the properties of standard particles can be substantially *different*. Consider, in particular, the hadrons containing a charm or a bottom quark, whose properties are well known from collider experiments. The lightest mode with a given quark content will always decay through a weak interaction, implying a relatively long lifetime ($c\tau = 0.1$–0.5 mm). Although at the Tevatron or the LHC very energetic heavy hadrons may define events with observable displaced vertices, such hadrons will never reach the calorimeters there. In contrast, when produced with energies above 10^8 GeV inside an extensive air shower (EAS) their decay length becomes larger than 10 km, and they tend to collide in the atmosphere instead of decaying. The collisions with matter of these long-lived heavy hadrons would introduce physics unseen at colliders. This physics will certainly occur in extensive air showers, and its inclusion in the simulation may be necessary to explain rare effects or just as a standard background in the search for genuine exotics.

The heavy quark inside an ultrarelativistic D or a B meson carries most of the hadron energy. If the meson collides with an air nucleus and *breaks* into several pieces, it is obvious that the piece carrying the heavy quark will take most of the energy after the collision. Therefore, at $E > 10^8$ GeV these particles become long lived and much more penetrating than a proton or a pion: a simulation seems necessary to establish whether heavy mesons are effective in taking a significant fraction of this energy deep into the atmosphere.

In addition, at energies above 100 GeV pions and kaons become less effective producing atmospheric muons and neutrinos (they tend to collide with air nuclei instead of decaying), and the spectral index in the lepton flux that they yield is reduced in one unit [8]. The prompt decay of charmed hadrons has been extensively studied [9] as the dominant source of leptons at PeV energies (see also [10]). The contribution from non-prompt charm (decaying after one or several collisions in the air), however, may be not negligible, specially at higher energies, and its inclusion in the simulation requires an estimate of propagation effects.

In this article we report on the inclusion of heavy-quark production and propagation in the air shower simulator AIRES [1]. In particular, we have developed a hadronic interaction preprocessor (HQIP, for Heavy Quark Interaction Preprocessor) that simulates the collisions

of heavy hadrons in the atmosphere or invokes the usual hadronic packages (SIBYLL [3] or QGSJET [4]) for collisions of nucleons and light mesons. When using HQIP, the charm production option in the external hadronic package is set to disabled. Instead, we have included a module that simulates the production of charm and bottom hadrons in the collisions of light hadrons with air nuclei, as explained in the next section.

AIRES [1] provides full space-time particle propagation in a realistic environment, taking into account the atmospheric density profile, the Earth's curvature, and the geomagnetic field. The new version of AIRES used in this work recognizes and fully propagates photons, electrons, positrons, muons, neutrinos, pions, kaons, eta mesons, lambda baryons, nucleons, antinucleons, nuclei up to $Z = 36$, as well as D and B mesons, and Λ_c baryons and tau leptons (which may appear in D_s decays). AIRES is able to process complex decay schemes with a large number of branches, as it is the case for heavy hadrons. Nucleus-nucleus, hadron-nucleus, and photon-nucleus inelastic collisions with significant cross-sections are taken into account, although the production of heavy quarks in nucleus-nucleus and photon-nucleus collisions has not been implemented yet.

This article is organized as follows. In section 2 we discuss in some detail the production cross sections and the inelasticities in heavy meson collisions with air nuclei that we have used. In section 3 we study the energy and atmospheric depth of heavy hadron production and decay for a vertical proton primary of fixed 30 EeV $= 3 \times 10^{10}$ GeV energy. Finally, we discuss the spectrum of muons and the production of very energetic tau leptons from heavy quark decays for the same proton primary.

2 Charm and bottom production and propagation

Heavy-quark production by cosmic rays has been considered by a number of groups (see [11] for a review). We will base our cross sections on the color dipole picture [12] described in detail in [13, 14], which is a perturbative QCD framework that incorporates in a simple way saturation and nuclear effects and is expected to be valid at very high energies. Within this picture a gluon carrying a fraction x_1 of the projectile energy fluctuates into a $Q\bar{Q}$ dipole that interacts with the gluon field ($x_2 \ll 1$) in the target and evolves into hadrons. GM [13] and ERS [14] provide the inclusive differential cross section $\mathrm{d}\sigma^{Q\bar{Q}}/\mathrm{d}x_F$ in proton–air collisions, where the Feynman variable $x_F = x_1 - x_2 \approx x_1$ gives the fraction of incident energy taken by the heavy-quark pair. The results by ERS at 10^{10} GeV and $x_F \sim 0.2$ are a factor of 4 larger than the ones by GM, something that could be expected given the uncertainty in the gluon distribution at small x and the low factorization scale ($\sim 2m_c$) involved in the calculation. We have averaged their results and plot in Fig. 1 (upper lines) the differential cross section for a 10^{10} GeV incident proton. The pair energy ($x_F E$) will then be distributed between the

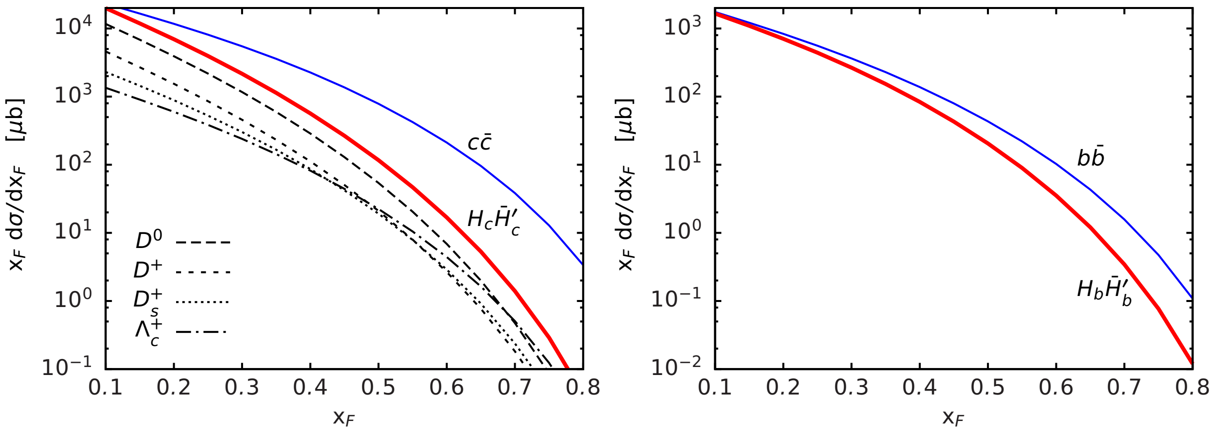

Figure 1: Differential cross section for $c\bar{c}$ (left) and $b\bar{b}$ (right) production in p–air collisions for an incident energy of 10^{10} GeV. The upper line gives the fraction x_F of energy taken by the $Q\bar{Q}$ pair, whereas the lower (thick) line gives the energy taken by the two hadrons after fragmentation. In dashes we plot the cross section for the production of each charmed species.

two heavy quarks. In particular, we assume that the fraction y of energy taken by each quark follows a flat distribution between $y_{\min,\max} = 0.5(1 \mp \sqrt{1-4\epsilon^2})$, with $\epsilon = m_Q/m_{Q\bar{Q}} \approx 0.3$.

Once produced the heavy quarks will fragment into hadrons. For the charm quark we have used the Kniehl and Kramer parametrization [15], including the fragmentation into D^0, D^+ and D_s^+ mesons and Λ_c^+ baryons (plus the corresponding antiparticles for $\bar{c}$). In Fig. 1–left we plot the fraction of energy taken by the hadron pair ($H_Q\bar{H}'_Q$) together with the relative abundance of each species in 10^{10} GeV p–air collisions. For the bottom quark (see [16]) we consider only fragmentation into B^- or $\bar{B}^0$ mesons, with equal frequency and a fragmentation function $D_b(z) = Nz^{13.7}(1-z)$, where $z = E_H/E_Q$. In Fig. 1–right we plot the fraction of energy taken by the pair of B mesons after the $b\bar{b}$ pair has been produced.

We have included in AIRES the production of heavy-hadron pairs in all collisions with incident energy above 10 TeV and considered only pairs carrying more than 1% of the projectile energy. These thresholds ensure the inclusion of all the effects that are relevant in air shower simulations and avoide complicating unnecesarily the procedure. Dividing by the total (inelastic) p–air cross section we obtain the probability to produce pairs of charm or bottom hadrons with $x_F > 0.01$. In Fig. 2 we plot this probability for different incident energies between 10^4 and 10^{11} GeV. The same production probability in the interactions of neutrons, charged pions and kaons with air has been assumed.

AIRES allows then the heavy hadrons either to decay or to collide with an air nucleus. In the case of a collision, we have taken the inelasticity and the interaction lengths for charm

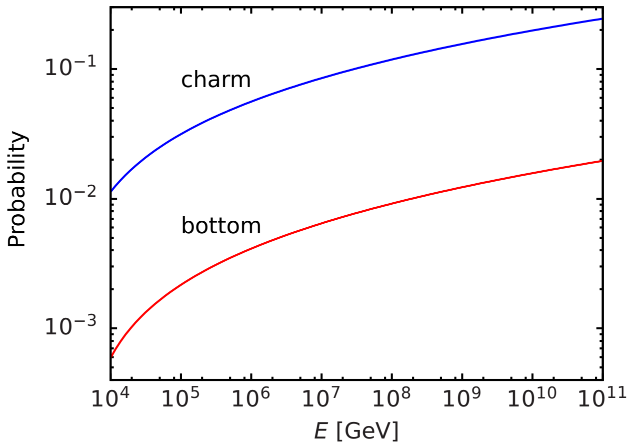

Figure 2: Probability to produce a charm or a bottom pair carrying more than 1% of the proton energy in p–air collisions.

and bottom hadrons from [17] and [18], respectively. For example, a D meson after a 10^9 GeV collision could keep around 55% of the initial energy, whereas a B meson will typically exit with 80% of the incident energy after colliding with an air nucleus. In contrast, the leading meson after a 10^9 GeV pion collision would carry in average just 22% of that energy.

3 Heavy-quark production and evolution in air shower development

To study the heavy hadron production and evolution inside the shower, we have generated 10,000 vertical showers initiated by a 30 EeV proton primary, simulated down to sea level.

In Fig. 3–left we plot the average number of charmed hadrons produced per shower in bins of 100 g/cm^2 and half a decade of energy. For example, from the plot it follows that around 0.37 charmed hadrons of $10^{7.5}$–$10^{8.0}$ GeV are produced per shower at atmospheric depths between 100 and 200 g/cm^2. These hadrons are produced in secondary collisions and also through the decay of B mesons (most of the high-energy charmed hadrons beyond 600 g/cm^2 come from B decays).

Adding bins we find that an average 30 EeV shower contains 0.9 charmed hadrons of energy above 10^8 GeV, and 6% of them are produced beyond 200 g/cm^2. The total energy transferred into these very energetic hadrons is 4.1×10^8 GeV, i.e., 1.4% of the energy of the primary proton. Concerning charmed-hadron decay, we plot in Fig. 3–right its depth and energy distributions. We find an average of 2.1 charmed hadrons of energy above 10^5 GeV decaying after 600 g/cm^2. They carry a total energy of 5.7×10^6 GeV beyond that

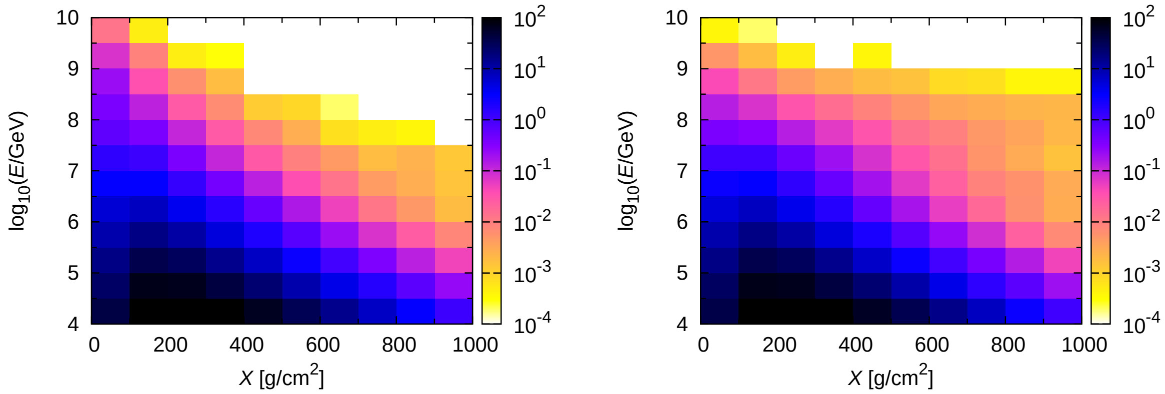

Figure 3: Average number of charm hadrons produced (left) and decayed (right) per bin of energy and atmospheric depth.

atmospheric depth.

Bottom hadrons are more rare in these showers, but their effect tends to be more *radical*. We plot the depth and energy distributions for their production (Fig. 4–left) and their decay (Fig. 4–right) for 30 EeV vertical showers. We find around 76 B mesons of energy above 10^8 GeV per 1000 showers, with an average production depth of 97 g/cm^2. This means that only 8% of the 30 EeV showers include such an energetic bottom hadron. Given the higher elasticity in their collisions, these B mesons reach deeper in the atmosphere than charmed hadrons before they decay. In particular, we find around 32 hadrons per 1000 showers decaying at atmospheric depths beyond 600 g/cm^2 with energies above 10^6 GeV, and 2 hadrons of energy above 10^7 GeV reaching the ground at 1000 g/cm^2.

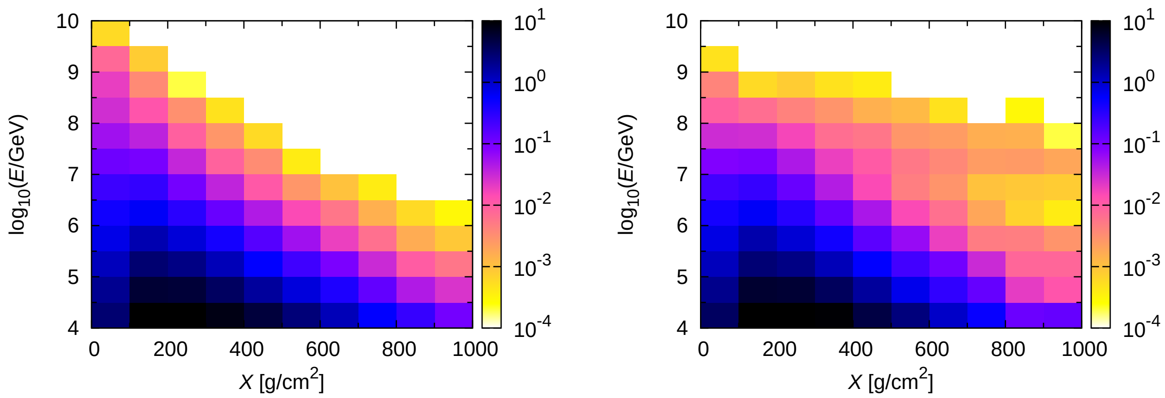

Figure 4: Average number of bottom hadrons produced (left) and decayed (right) per bin of energy and atmospheric depth.

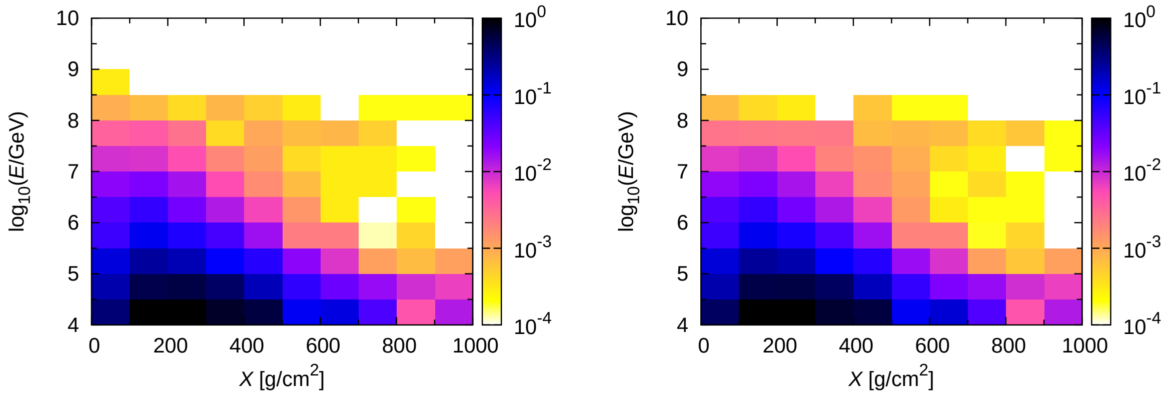

Figure 5: Average number of tau leptons produced (left) and decayed (right) per bin of energy and atmospheric depth.

4 Tau leptons and muons

In this section we present the frequency of tau lepton events and the average muon energy distribution from our simulation of 30 EeV vertical proton showers.

Tau leptons are mainly produced in D_s decays. They may introduce interesting effects because their decay length ($c\tau = 87\ \mu$m) reaches 5 km at 10^8 GeV. In Fig. 5–left (right) we plot the point and energy where they are produced (decay) inside the shower. We find 46 tau leptons of energy above 10^7 GeV per 1000 showers. They are produced at an average depth of 270 g/cm^2 and decay at 320 g/cm^2, in particular, 18% of them decay after 600 g/cm^2. For example, in the energy bin between 10^8 and $10^{8.5}$ GeV we obtain 4.3 tau leptons per 1000 vertical showers, with 1.6 of them reaching the ground. Therefore, the frequency of very energetic taus produced in EAS that decay near the ground is similar to the frequency of the analogous B-meson events.

Muons, on the other hand, are a key ingredient in air-shower simulations. Although the presence of heavy hadrons will not introduce significant differences in the *total* number of muons at the ground level or in their lateral distribution, there are other observables that may be more sensitive to these heavy hadrons. In particular, one could expect two types of effects.

- *Rare events with late energy deposition* from the decay of a heavy meson or a τ lepton. A 10^8 GeV deposition relatively near the ground would produce muons and other charged particles that could change significantly the shower profile seen in the fluorescence telescopes and/or the temporal distribution observed in the surface detectors. The frequency of these events can be estimated from our results above and in previous

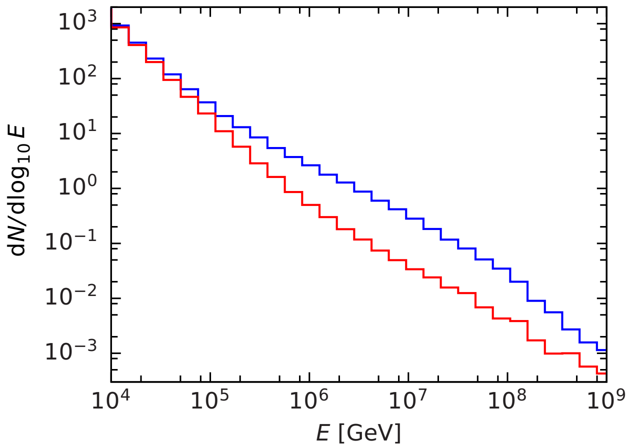

Figure 6: Average energy distribution of ground muons from a 30 EeV proton shower simulated with (upper histogram) and without (lower histogram) the production, propagation and decay of heavy hadrons.

sections.

- *Leptons of PeV energies.* At very high energies pions tend to collide in the air instead of decaying thus becoming a less effective source of muons [9, 10]. This shows up clearly in Fig. 6, where we plot the energy distribution of muons reaching the ground for a 30 EeV proton primary. The distribution in showers simulated using HQIP is almost 10 times larger than the one with no heavy quark production at PeV energies. These very energetic muons may be observable at neutrino telescopes [19], and they could be used to estimate the correlated neutrino flux.

5 Summary and discussion

At energies above 10^8 GeV hadrons containing a charm or a bottom quark become long lived, and it is then necessary to implement their collisions with air nuclei in air shower simulations. Although the interactions with matter of D and B mesons are not observable at colliders, one expects that they are much more elastic than pion or proton collisions.

The main effect of these particles would derive from their ability to transport energy deep into the atmosphere. Since the fraction of events with a very energetic heavy hadron is small, one can not expect significant differences in the features of the average shower. In particular, we have studied common observables like the lateral and the longitudinal distributions of charged particles, and in all cases we could not observe any relevant differences due to heavy

quark effects. Instead, one could look for anomalous events with late energy deposition caused by their decay.

We have included both the production and the propagation of heavy hadrons in a new version of AIRES. To illustrate the results, we have simulated vertical showers of fixed 30 EeV energy. We find around one D meson of energy above 10^8 GeV per shower, or just one B meson in this energy range per 13 showers. A few per mille of these air showers includes a B meson of energy above 10^7 GeV hitting the ground at 1000 g/cm^2. The frequency of very energetic tau leptons from D_s decays reaching large atmospheric depths is slightly higher.

The inclusion of heavy hadrons in AIRES opens the possibility to search for charm and bottom effects in astroparticle experiments.

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